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MultiTip: A multimodal mechano-thermal soft fingertip

Gabor Soter¹, Andrew Conn², Helmut Hauser¹, Nathan F. Lepora¹ and Jonathan Rossiter¹

Abstract—In this paper we present MultiTip, a novel multimodal mechano-thermal soft tactile fingertip. In comparison to previous multimodal sensing techniques, our device uses a single optical sensor to detect both mechanical deformation and temperature change simultaneously. Our fingertip is an improved version of the TacTip, a tactile fingertip that combines compliant materials and optical tracking to perform a variety of tasks such as object manipulation, contact and pressure sensing. However, temperature sensing, which is one of the last remaining challenges to mimic the full sensory capabilities of the human finger, has been neglected as a modality in optical tactile sensors. In this work we present a novel design and fabrication method for the skin of the TacTip that enables the device to simultaneously sense local temperature change while concurrently transducing the mechanical aspects of touch. This is achieved by creating a smart skin that changes its colour due to temperature change. MultiTip achieves multimodality without adding another sensing element and is therefore ideally suited to miniaturizing the sensor. We present the characteristics of the proposed sensor in sensing mechanical deformation and temperature at the same time. Finally, we demonstrate two possible real-world applications. MultiTip thus makes an important step towards full biomimicry of the human tactile fingertip.

I. INTRODUCTION

In order to function effectively and safely in a human environment, robots need to be able to perform the same complex functions of sensing and manipulation as humans [1]. A key requirement for robotic fingertips is the ability to sense force, vibration and temperature in order to perform high-level tasks, such as manipulation, surface roughness detection and material identification [2]. For most of these tasks, the sensory modalities are synergetic. For example, material identification requires sensing force, vibration and temperature at the same time. The force sensor provides feedback on the stiffness of the material and sensing the vibration helps to detect different textures. The temperature measurement is also important since for materials with lower heat conductivity (e.g. wood) it takes more time to change temperature than for materials with higher heat conductivity (e.g. metal) [3]. Ideally, an artificial fingertip should have all these capabilities to gain the full competency of the human

sense of touch, while also being robust, scalable in size, and have a fast response.

Designing artificial fingertips that mimic the human fingertip is challenging. There is a wide variety of tactile sensing technologies available using different transduction mechanisms such as optics, piezoelectric, capacitance, ultrasound, conductive polymers etc. [4]. These provide some information, but for truly autonomous robots that should be able to deal with complex tasks at the same level as humans, there is a need for multimodality. While a wide variety of sensors have been developed, only a few of these combine the multimodal sensory capabilities of the human skin [2], [5]. These devices usually contain two or more sensing elements, which results in a complex design and processing.

In this paper we present an improved, multimodal design of a soft artificial fingertip, TacTip, which is a biologically-inspired sensing device based on the epidermal layers of the human skin [6]. The skin of the TacTip is highly deformable. This deformation is amplified by pins located internally on the skin and the movement of these pins is tracked by a camera. The original sensor has a black skin filled with gel in order to provide better tactile feedback. In this study we integrate a colour changing, thermochromic elastomer compound to the skin to visualise the change of temperature (see Figure 1). We remove the gel because of its high heat capacity and instead we fill the sensor with air. Furthermore, we add a thin, external black layer to the outer skin in order to reduce the effect of the ambient light. The colour change of the skin is recorded by the same camera that tracks mechanical movement.



Fig. 1: The skin of the sensor is made of hyperelastic, thermoactive material, therefore, it is able to provide simultaneous information on deformation and temperature change.

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Our design not only provides a solution for the multimodality problem, but it does so without requiring any additional sensing element. This means that our design can be easily miniaturised, in contrast to many other multimodal fingertips that are limited in size simply because there is not enough space for all the sensors [3].

In order to measure deformation and temperature change, the camera image is postprocessed using two different algorithms. The deformation of the skin can be measured by tracking the pins, while change in temperature can be detected by analysing the colour of the rest of the skin.

In particular, the contributions of this paper are as follows:

- To the best of our knowledge, this is the first application of thermochromic powder in silicone for multimodal sensing.
- The image processing algorithm enables the sensor to detect mechanical deformation and temperature change simultaneously in real-time.
- We demonstrate real-world experiments in order to present the possible applications of the proposed sensor.

The remainder of this paper is as follows: in Section II we discuss some related work; in Section III we present the design of the sensor and the image processing algorithms; in Section IV we characterise the sensor; finally, in Section V we present possible real-world applications.

II. RELATED WORK

A. TacTip

TacTip was first presented in [6] and both its hardware and software have been improved since then [7]. The first TacTip generation was used for shape recognition [8], manipulation [9], edge detection [10], object exploration [11] and topography reconstruction [12]. The image processing algorithm described in [10] used morphological operators in order to detect edges in real time, which was a clear need for the robotic fingertip. Later, the sensor was integrated with soft robots [13] and robotic hands [9]. In order to detect surface texture, the previously smooth outer skin surface was improved by bumps positioned directly over the papillae pins [14], [15]. This is a biologically-inspired improvement: the human skin structure is integral to its sensing mechanisms. The results have shown that the sensitivity could be increased by modifying the hardware of the TacTip. Other studies investigated how the sensitivity can be increased by improving the software by superresolution [16], which takes advantage of the soft structure of the tactile sensor surface to improve the perceptual acuity. Recently, TacTip has won the first prize in an international competition on soft robotics [17].

B. Multimodal sensing

Several groups have sought to address the problem of multimodal sensing. Artificial skins with mechanical multimodal capabilities are presented in [18], [19] and [20]. Simultaneous measurement of contact forces, microvibrations and thermal fluxes are discussed in [2]. The biomimetic array BioTac has an elastomeric skin inflated by a conductive liquid over a bone-like core. A pressure transducer is used

to measure the microvibrations that propagate in the fluid and a thermistor is used to measure the temperature of the conductive liquid. The fabrication of BioTac is challenging, with very small space for all the sensors. Another method to fabricate multimodal tactile sensors is presented in [5]. The authors describe the design, fabrication process, and characterization of a multimodal tactile sensor made of polymer materials and metal thin film sensors. The multimodal sensor can detect hardness, thermal conductivity and temperature. A solution for multimodal whole-body-touch sensation for humanoid robots is described in [21]. The device, HEX-O-SKIN, is a small hexagonal printed circuit board equipped with multiple discrete sensors for temperature, acceleration, and proximity.

C. Thermoactive, colour changing materials

Thermoactive, colour changing powder or paint is not a commonly used material in robotics. They have been recently used in shape memory polymers in order to visualise actuation and to sense temperature [22]. In this case the colour changing effect enables the user to monitor the temperature and the phase change of the actuator.

Thermoactive powder is also used in prosthetics [23] to provide mechanical and physical properties for prosthetic devices that are comparable to the human skin. In this work the authors present a prototype which exploits thermoactive pigments to provide temperature monitoring during direct object touch.

III. SENSOR DESIGN

A. Structure

The working principle of the sensor is shown in Figure 2. The main components are the soft, thermoactive, colour-changing skin, a USB camera, white LEDs for illumination and a 3D printed case. The camera is able to capture the deformation of the pins and also the colour change of the skin at the same time. When the soft skin is deformed by an external object, the distances between the pins change and this is tracked by the visual sensor. The skin shown in Figure 1 is hyperelastic and easily deformable, but thick enough (~ 0.5 mm) to compensate against gravity. Moreover, the skin is thermoactive: when it is warmed up its colour changes from black to white (see Figure 2 (c)).

The colour changing ability of the skin enables it to sense mechanical and temperature change at the same time using the same sensor, i.e., the digital camera. The camera is placed at a distance of approximately 70 mm from the centre of the skin in order to capture the whole pin array. Three white LEDs are positioned inside the case to illuminate the skin and their brightness can be controlled manually. In contrast to the previous versions of the TacTip sensor, the colour of the skin plays an important role in sensing; therefore, the lighting conditions need to be carefully set up. Furthermore, the skin of the original TacTip is completely black which means that it is not sensitive to the ambient light. However, in our case the skin is translucent affecting the image processing algorithm. In order to overcome this problem, we added an

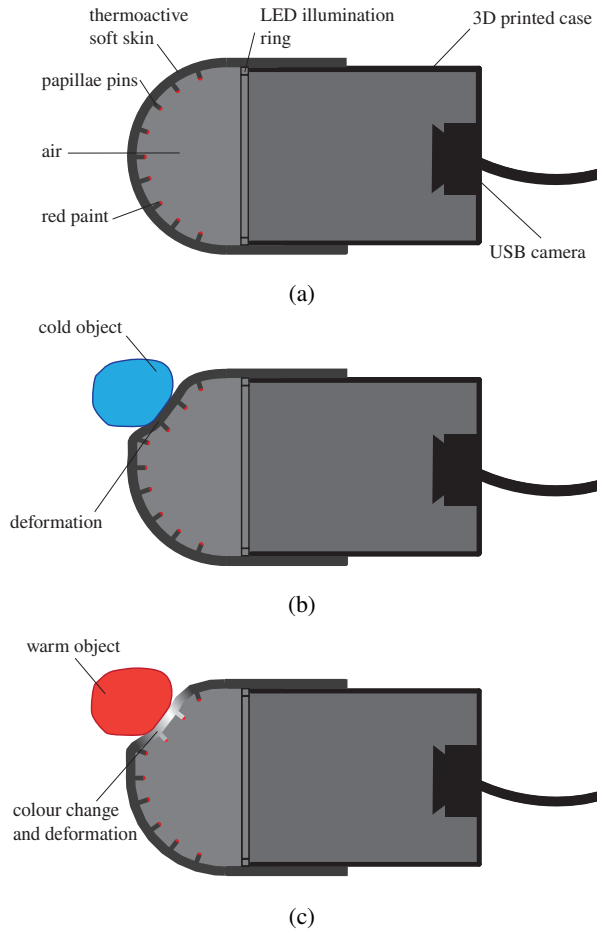


Fig. 2: The design and the working principle of the sensor. (a) The main components of the sensor are the thermoactive, colour-changing, soft skin with the radius $R = 20$ mm, a Microsoft VX-1000 USB camera, LEDs for illumination and a 3D printed case. (b) When an external object deforms the elastic skin, the position of the pins change and this can be tracked by the camera. (c) Depending on the temperature of the external object, the skin changes its colour, therefore, the image sensor can be used to detect both temperature change and skin deformation.

extra layer of stretchable, black silicone paint to the outside skin. The effect of the coating is shown in Figure 3.

B. Materials

The skin of the sensor was made of a two-component Vytaflex 30 elastomer. During the fabrication process, the elastomer was mixed with commercially available SFXC thermochromic powder. The activation temperature of the powder was 31°C . The colour of the powder was black when its temperature was below and white when it was higher than the activation temperature. This means that the sensor can operate only for binary temperature measurements. The device can therefore sense whether the temperature of the object it touches is below or above 31°C . We note that although the powder affects the mechanical properties of the

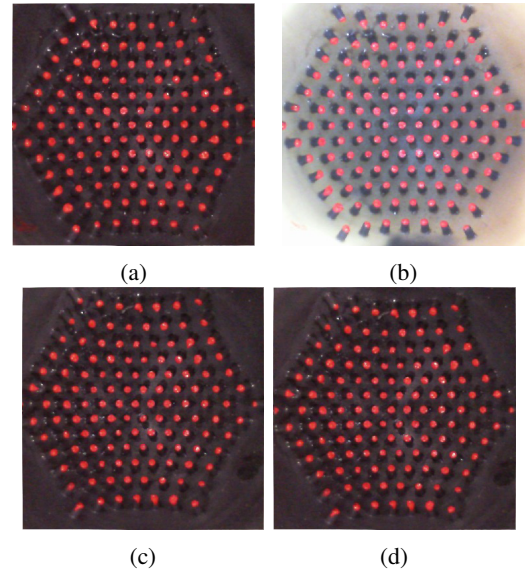


Fig. 3: The effect of the additional black coating. The images (a) and (b) represent skin without external coating in a dark box and in a bright environment, respectively. One can see that the lighting conditions have a significant effect on camera image. In order to solve this problem, a stretchable, black coating was added by spray painting the outside of the skin. (c) and (d) shows the skin in a dark box and in a bright environment.

skin, this is not significant and therefore this paper does not analyse the effect of the powder content.

The original version of TacTip is filled with an optically clear gel in order to provide better tactile feedback. However, in this case using gel is not beneficial since it has significant heat capacity and it makes the thermal processes and the colour change take a longer time. Details of the fabrication of the original TacTip is described in [6].

C. Algorithms

1) *Deformation*: The advantage of the proposed design is that the same camera can be used for sensing both the temperature and deformation. Therefore, the temperature field and deformation are measured using the same image. There are several existing algorithms [10], [14], [16] to measure the deformation of the skin. Since our background changes between black and white in case of temperature change, we had to extend the existing algorithms with additional filtering capabilities. First, the original image (390×430 pixels) was blurred with a kernel size of 21×21 pixels. The blur filter was used to reduce the noise and the glossy effect of the skin. The latter was especially important because the gel usually helps the TacTip to reduce internal reflection, but in our setup we could not use it because of its heat capacity. The background was subtracted from the original image by defining a mask based on colour data. Finally, an adaptive threshold and a contour finding algorithm was used to localise the markers. The steps of the image processing are shown in Figure 4.

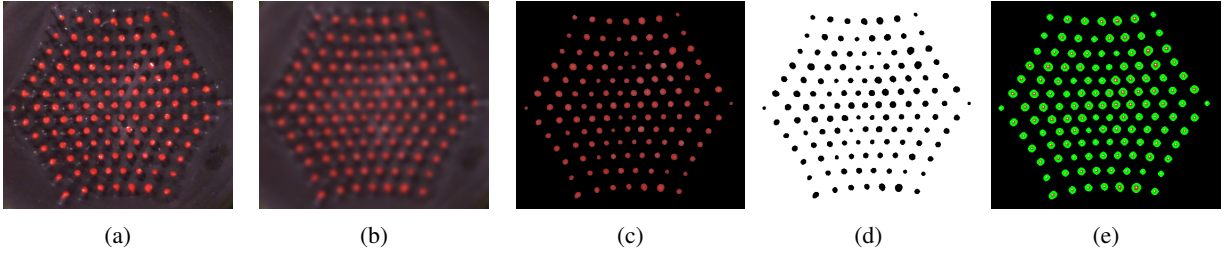


Fig. 4: The steps of the image processing for deformation measurement. First, the original image (a) was blurred in order to decrease the noise (b). Next, the background was removed using a colour mask (c) and an adaptive threshold filter was used to convert the image to grayscale (d). Finally, the contours of the pin are shown in green (e).

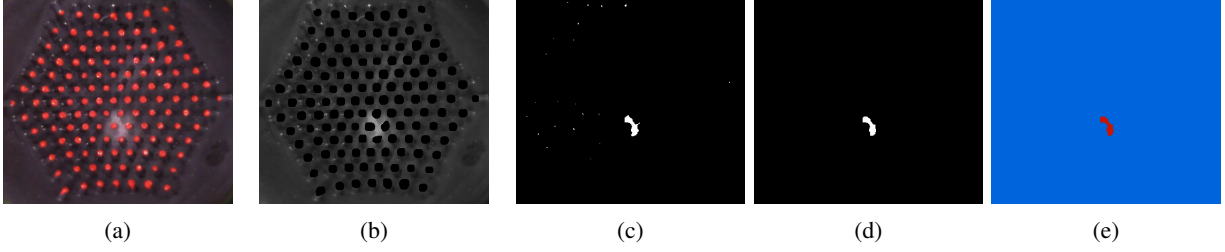


Fig. 5: The steps of the image processing for temperature measurement. The red pins were subtracted from the original image (a) and the image was converted to grayscale. (b) Next, a threshold filter was used in order to separate the white (warm) areas from the black (cold) ones (c) and an adaptive threshold filter was used to convert the image to grayscale (d). Finally, region of high temperature is shown in red (e).

2) *Temperature field*: In order to measure temperature change we used the same camera image as for deformation measurement. Here the red pixels were subtracted from the image and the remaining pixels were used to provide information on the temperature distribution. After the subtraction, the image was converted to grayscale and by using a threshold filter the white (warm) areas could be separated from the black (cold) ones. Again, we needed to remove those pixels that were false positives because of internal reflection. In this case we applied a dilation filter after we subtracted the pins, and additionally, after thresholding, an opening filter was applied to remove the small white areas. The steps are shown in Figure 5.

The spatial resolution of the sensor for tactile information relies on the papillae density and the image capture and processing system, while the resolution of the sensor for temperature information relies only on the resolution of the camera. The sensor presented in this paper had 127 papillae and the camera resolution was 390×430 .

IV. CHARACTERISATION

In this section we present some characteristics of the thermoactive skin. We analysed the skin in a temperature controlled environment where the ambient temperature was 23°C . We used a heat gun with the temperature 60°C for 12s to heat the skin and we recorded the temperature distribution on it with a thermal camera (FLIR E4). The results shown in Figure 6 and 7 are displayed from both thermal and normal cameras by combining distinct runs.

Figure 6 shows the maximum temperature of the skin over time. The process has five steps: before the heat gun is turned

on (A), when the heat gun is turned on (B), after the heat gun is turned off (C), when the skin is cooling but the maximum temperature is above the activation temperature (D) and when the skin is cooling and the maximum temperature of the skin is below the activation temperature. These steps are the shown in Figure 7. Before the heating, the skin is completely black. By turning on the heat gun the skin warms up very quickly and changes its colour almost immediately. However, the cooling process takes much longer.

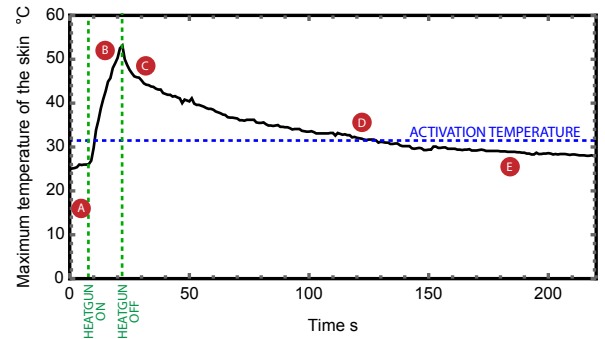


Fig. 6: The maximum temperature of the skin during the heating process. There are five steps: before the heat gun is turned on (A), after the heat gun is turned on (B), the heatgun is turned off (C), the skin is cooling down but the maximum temperature of the skin is above the activation temperature (D), the skin is cooling down and the maximum temperature of the skin is below the activation temperature (E). The colour and temperature change of the skin are shown in Figure 7.

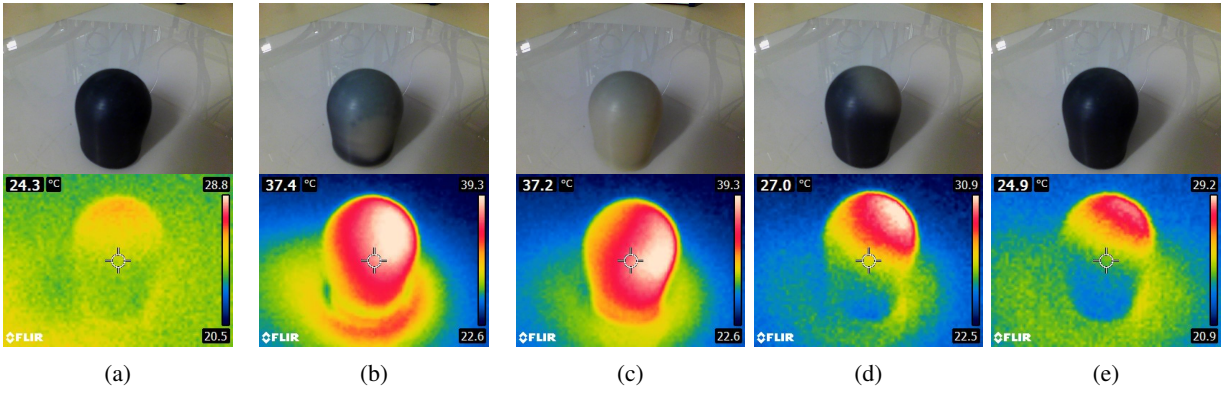


Fig. 7: Temperature distribution and colour change of the skin. A heat gun was used in order to warm up the skin and it was placed next to the thermal camera, approximately 50 mm away from the skin. Each image pair labelled with letters (a-e) represents a snapshot of the steps explained in Figure 6, i.e., A-E respectively.

V. APPLICATIONS

In this section we present two possible real-world applications. The first belongs to robotic automation. In this case, the sensor is able to distinguish between two electronic components (Figure 9 (c) and (d)) that look and feel the same, but the microchips on them have different temperatures (one of them is overheated, the other one is normal). Figure 9 (a-b) shows the difference between the two images captured by the camera. The white (warm) area can be detected using the image processing algorithm described in Section III.

The second possible application is to determine whether the robot touched a human or something else. Robots around us in the future will have to be safety critical in order to ensure that they do not cause harm. This means that they need several sensors that provide the same information. In this case, the robot could use the temperature information in order to double-check whether it touches a human body. This is shown in Figure 8 and 9. In both cases the deformation of the pins look similar (Figure 9 (e) and (f)), however, there is a difference in the thermoactive background, thereby showing effective determination of human touch (Figure 9 (g) and (h)). This method can be used in any cases when the sensor is in contact with the human skin and there is no thermal insulation between them (e.g. gloves, clothes).

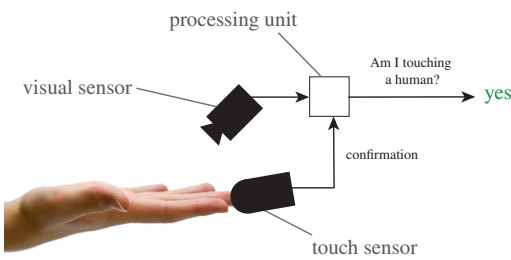


Fig. 8: Possible application of the proposed fingertip. The multimodal sensor is used to confirm that the robot touches a human hand.

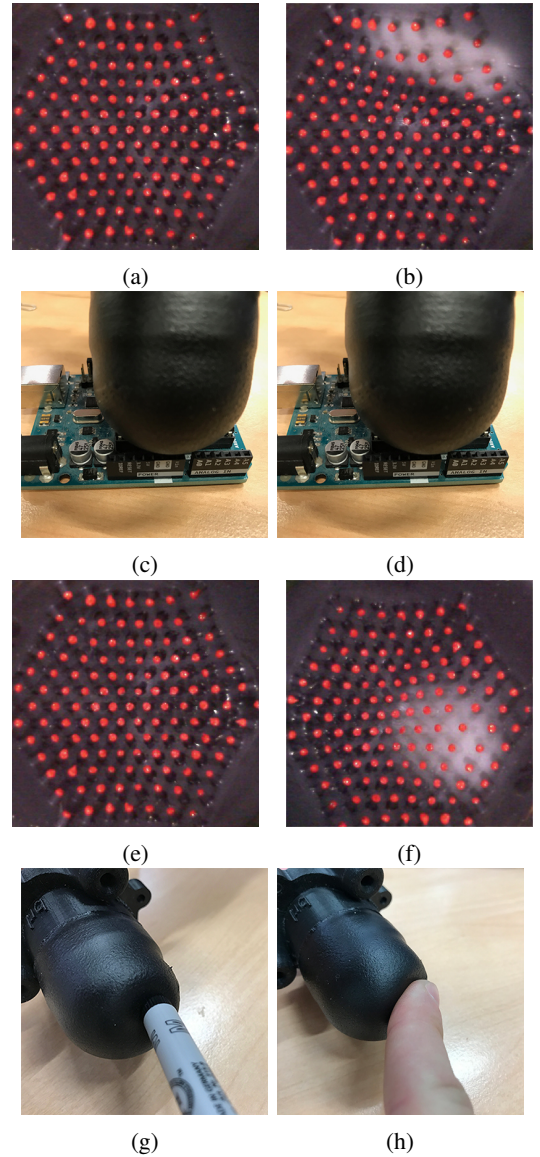


Fig. 9: Possible applications for robotic automation (a-d) and human-robot interaction (e-h).

VI. CONCLUSION

In this work we present MultiTip, an improved design of the TacTip sensor. In contrast to previous versions, our design is able to detect not only mechanical deformation, but temperature change as well. This was achieved by using thermoactive powder in the skin of the sensor. As a result, the skin can change its colour when it is in contact with a warm ($>31^{\circ}\text{C}$.) object. The colour change is captured by a camera and an image processing algorithm was written to distinguish between the cold and warm areas.

We foresee several ways in which the device can be improved further. Currently, only a binary temperature measurement is available. The sensor is able to detect whether it touches a warm or cold object, but it cannot measure the exact temperature. An improvement could be to use various thermochromic powders with different colour and activation temperatures. Another limitation is that the cooling process takes a long time and the rate of change depends on the ambient temperature. This could be solved by keeping the temperature of the skin just around the activation temperature by active cooling or heating.

The proposed sensor has many benefits compared to other multimodal fingertips. It is an easy-to-fabricate, low-cost device and it does not require any additional sensing element. This property is especially important when the fingertip has to be scaled (e.g. for prosthetics). Other multimodal, artificial fingertips are not easily scalable, simply because there is no space for all the sensors. Our sensor solves this problem since the camera captures both the deformation and temperature change.

An interesting extension of the present work would be to sense other physical quantities as well, e.g. pH value, electric potential, magnetic field etc. For example, by adding indicators that change their colour in response of pH value, it would be possible to measure the pH value of the environment only using the camera.

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